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Report No. 80-5

Optimum Swath Widths and Application Rates for Selected Aircraft and Meteorological Regimes

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DISCLAIMER STATEMENT

Report 80-5

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OPTIMUM SWATH WIDTHS AND APPLICATION RATES FOR SELECTED AIRCRAFT AND METEOROLOGICAL REGIMES[1]

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ABSTRACT

A computerized atmospheric dispersion and canopy-penetration model is used to demonstrate the feasibility of determining optimum swath widths and pesticide application rates for planning and conducting selected aircraft spray operations over spruce-fir forests during morning meteorologicql regimes. The model calculations also provide estimates of the spray deposition within the forest canopy as well as the deposition downwind from the spray block due to spray drift.

INTRODUCTION

The USDA Forest Service (FS) has been using mathematical dispersion models to predict the transport and deposition of insecticide sprays released by aircraft over forests since 1971. Under the USDA Expanded Douglas-fir Tussock Moth Research and Development Program (Brookes, Stark and Campbell, 1978), a study was performed to further refine and verify the performance of two models which are used in conjunction to predict the dispersion and canopy penetration of insecticidal sprays in forest canopies. The results of this study, described by Dumbauld, Rafferty and Bjorklund (1977), demonstrated the feasibility of using the Cramer/Barry/Grimm (CBG) model in planning and conducting aerial spray projects.

In this report, we describe the results of using the CBG model to determine optimum swath widths and spray application rates which achieve a uniform coverage of 20 to 25 drops per square centimeter at the top of the forest canopy under various meteorological conditions for five different types of spray aircraft. These aircraft (TBM, C-54, Constellation, Bell 205 and Thrush) are frequently used to spray large tracts of forest in the State of Maine. In this study, we have assumed that

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the aircraft spray Sevin 4-oil over a Maine-type forest, idealized for modeling purposes.

Details of the procedures used in obtaining wind speed inputs used in the model calculations are presented in Appendix A and Appendix B contains the data used to develop the source characteristics of each aircraft. Details of the mathematical modeling techniques used in the CBG model are given in the report by Dumbauld, Rafferty and Bjorklund (1977).

METEOROLOGICAL REGIMES, FOREST AND AIRCRAFT CHARACTERISTICS

Meteorological Regimes

Spray projects are usually conducted in the early morning hours in the presence of low wind speeds and stable air above the canopy which tend to minimize spray drift. Sometimes the spray activities extend into later morning hours with higher wind speeds and turbulence levels above the forest. Limited spraying can be conducted in the later afternoon under favorable weather conditions. However, the scope of this project was limited to a study of morning regimes. We selected the following four morning meteorological regimes for consideration in this study:

- -Early morning hours with very light wind speeds within and above the canopy

- -Early morning hours with light wind speeds within and above the canopy

- -Late morning hours with light wind speeds within and above the canopy

- -Late morning hours with moderate wind speeds within and above the canopy

The procedure used to define the wind speed profiles for these regimes is explained in detail in Appendix A. Briefly, we first arbitrarily assigned mean wind speeds $\bar{u}_R\{z_R=2m\}$ at a reference height of 2 meters in a large open area for the four meteorological regimes. We then assigned wind power-law coefficients p to define the vertical wind profile over open areas to a height of three times the height of the top of the canopy. A zero-plane displacement profile suggested by Oliver (1971) for use over forest canopies was then used to calculate the wind profile down to the forest canopy. Next, a mean wind profile within the canopy was adjusted to the wind speed at the top of the canopy and used to specify wind speeds within the canopy. The values assigned to $\bar{u}_R\{z_R=2m\}$ and p are shown in Table 1. The CBG dispersion model uses a transport

Table 1. Meteorological specifications for four regimes used in the study.[3]

Time of Morning	Wind Speed Category	$\bar{u}_R\{z_R=2m\}$ mi/h	$\bar{u}_R\{z_R=2m\}$ m/s	p	H_m (m)	$\sigma_A\{\tau_o=600s\}$ (deg)	σ_E (deg)
Early	Very Light	1.5	0.67	0.25	115	6.5	2.2
Early	Light	3.0	1.34	0.25	115	6.5	2.2
Late	Light	3.0	1.34	0.15	315	15.0	5.0
Late	Moderate	6.0	2.68	0.15	415	10.0	3.3

[3] See the discussion of meteorological regimes in the text for a definition of parameters

wind speed which is the mean wind speed between the spray cloud stabilization height and the height of the aircraft. The transport wind speed used in the CBG dispersion model was calculated from the wind speed profile obtained by the procedure outlined above. Since the aircraft height and spray cloud stabilization height depend on the type of aircraft, there are different transport wind speeds for each aircraft and each meteorological regime. The transport wind speeds ($\bar{u}_T$) used in the calculations are given in Table 2.

Values of the depth of the surface mixing layer H_m, the standard deviation of the wind azimuth angle measured over a reference time of 600 seconds $\sigma_A\{\tau_0=600s\}$, and the standard deviation of the wind elevation angle σ_E used in the model calculations are given in Table 1.

Forest Characteristics

All the calculations were made for a spruce-fir forest comprised of 50-foot (15.2-m) trees with a stand density of 600 stems per acre. The shape of the typical tree in the forest is shown in Figure 1. Tree envelope widths as a function of tree height required by the canopy penetration model, based on the shape of the tree shown in Figure 1, are given in Table 3. The probability of penetration (PRPEN) was set equal to 0.38 and the diameter of tree elements used in calculating impaction efficiency was set equal to 13 centimeters.

Aircraft and Spray Characteristics

The aircraft characteristics used in the model calculations are shown in Table 4.

As noted earlier, the model calculations are made assuming Sevin 4-oil is sprayed from each aircraft. Because of the relatively low volatility of oil, no evaporation of drops was assumed to occur. The mass and number distributions of drops in the spray cloud produced by each aircraft are described in Appendix B. The number distribution of drops was used in the calculation of drop deposition and the mass distribution was used to calculate mass deposition for comparison with the calculated drop deposition. The cumulative number distribution of drops for the 5 aircraft are summarized in Figure 2.

RESULTS OF THE MODEL CALCULATIONS

Optimum Swath Widths and Application Rates

The meteorological, aircraft, spray and forest characteristics described above were used in the CBG model to estimate swath widths and application rates required to achieve a deposition level of 20 to 25 drops per square centimeter at the top of the canopy. In each case, the aircraft flight line was assumed to be perpendicular to the mean wind

Table 2. Transport wind speeds used in the model calculations.

Time of Morning	Wind Speed Category	Aircraft Type	Mean Transport Wind Speed ($\bar{u}_T$)	
			mi/h	m/s
Early	Very Light	TBM	2.86	1.28
		C-54	3.38	1.51
		Constellation	3.38	1.51
		Bell 205	2.48	1.11
		Thrush	2.46	1.10
Early	Light	TBM	5.70	2.55
		C-54	6.76	3.02
		Constellation	6.76	3.02
		Bell 205	4.99	2.23
		Thrush	4.94	2.21
Late	Light	TBM	4.18	1.87
		C-54	4.83	2.16
		Constellation	4.83	2.16
		Bell 205	3.27	1.66
		Thrush	3.67	1.64
Late	Moderate	TBM	8.37	3.74
		C-54	9.66	4.32
		Constellation	9.66	4.32
		Bell 205	7.40	3.31
		Thrush	7.36	3.29

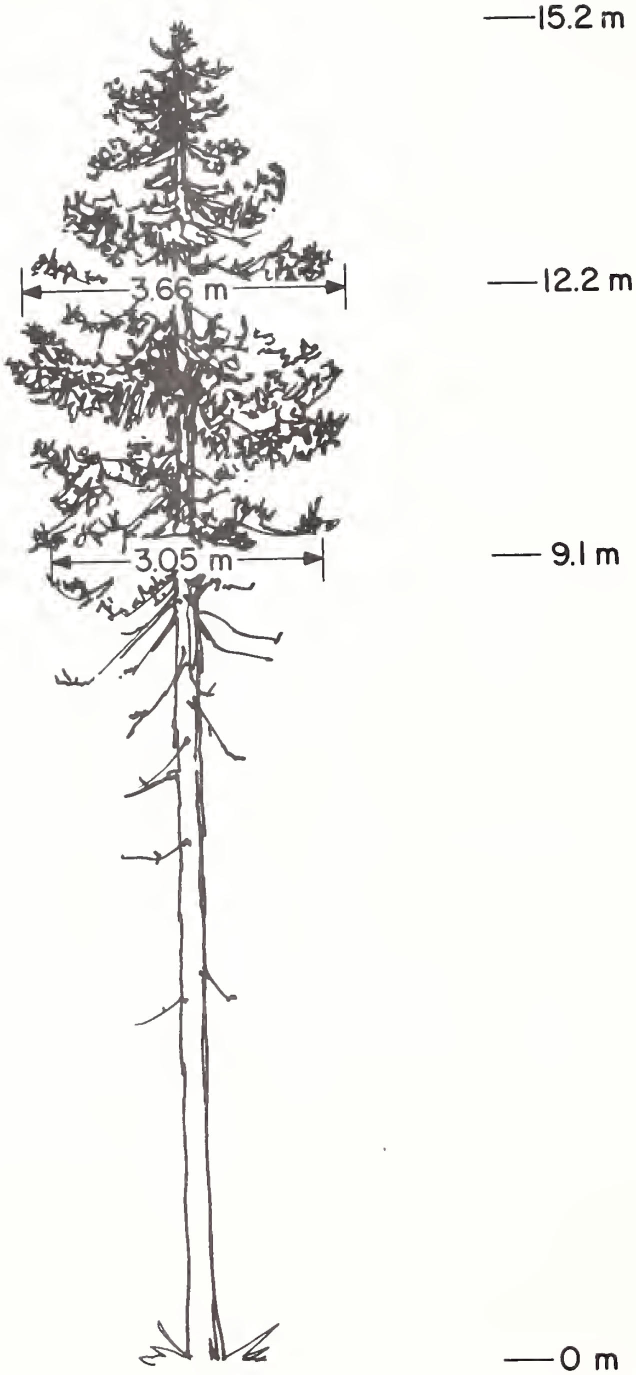

Figure 1. Profile for the typical tree used in the model calculations.

Table 3. Tree envelope diameters used in the canopy penetration model.

Height in Canopy (m)	Tree Envelope Diameter (m)
1	0.500
2	0.500
3	0.500
4	0.500
5	0.500
6	0.500
7	0.500
8	0.500
9	3.408
10	3.494
11	3.579
12	3.658
13	2.438
14	1.220
15	0.100

Table 4. Aircraft characteristics.

Aircraft Type	Weight (kg)	Wing or Rotor Span (m)	Speed		Release Height Above Canopy	
			(mi/h)	(m/s)	(ft)	(m)
TBM	6824	16.46	165	73.76	100	30.48
C-54	21636	34.62	180	80.46	200	60.96
Constellation	39000	35.81	200	89.40	200	60.96
Bell 205	3917	14.63	100	44.70	50	15.24
Thrush	2932	13.41	100	44.70	50	15.24

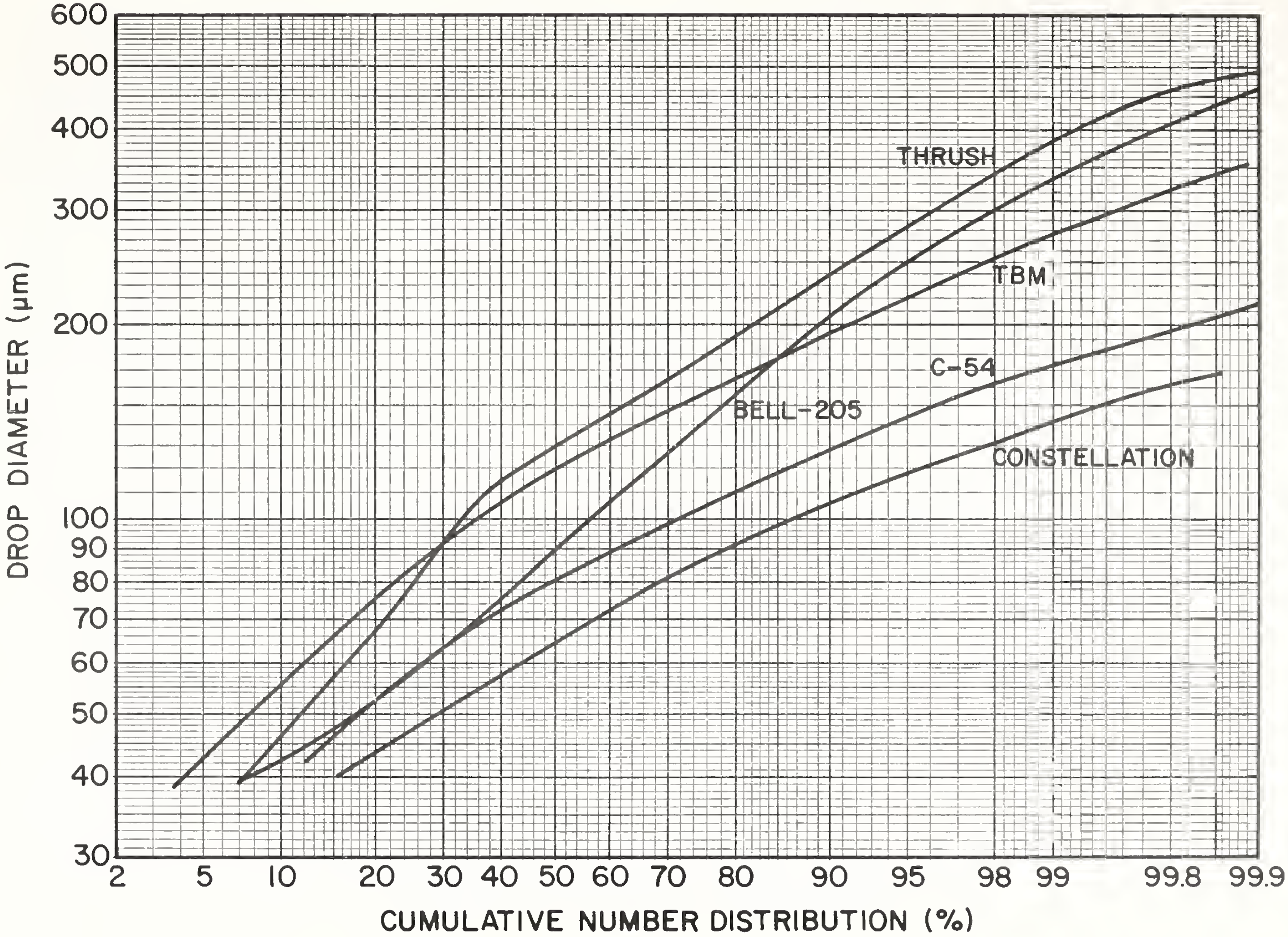

Figure 2. Cumulative number distribution for Sevin 4-oil spray drops produced by the various aircraft.

direction with the first swath occurring at the downwind edge of the spray block. The width of the spray block in the direction of the wind was assumed to be 9.7 kilometers (6 miles) for the TBM, C-54 and Constellation and 3.2 kilometers (2 miles) for the Bell 205 and Thrush aircraft. The length of the spray line perpendicular to the wind was set to a large value so that dispersion from the ends of the line (edge effects) did not affect the results. Initial estimates of the requisite swath width and application rate were made and the deposition level at the top of the canopy calculated. If the calculated deposition level was less than 20 to 25 drops per square centimeter or the variation at the canopy top between the troughs and peaks of the deposition pattern was greater than a factor of 1.4, the calculation was repeated until a satisfactory result was achieved. For example, the final results for a C-54 aircraft spraying in the early morning under very light wind speeds are shown in Figure 3. The swath width used to obtain the results shown in the figure was 244 meters (800 feet) and the application rate was 20 ounces per acre. In Figure 3, the wind direction is from left to right and the C-54 flight lines are alternately directed into and out of the plane of the figure. The peaks in the deposition level occur downwind from each flight line and represent the major contribution to the deposition level from that flight line as well as from all flight lines subsequently flown upwind from that point. Inspection of Figure 3 shows that the deposition level remains above 25 drops per square centimeter except at the upwind edge of the spray block (left-hand portion of Figure 3). Once an application rate and swath width were determined for an aircraft spray release in the early morning hours under very light winds, the application rate was held constant for determining the swath widths required to achieve the requisite deposition levels under the other meteorological regimes.

The results for all aircraft and meteorological conditions are presented in Table 5. The C-54 and Consellation aircraft have the largest swath widths and lowest application rates required to achieve a deposition level of 20 to 25 drops per square centimeter because their spray distributions are comprised of smaller drops and they fly at greater altitudes than the other aircraft.

Figure 3 and similar curves of the deposition level at the canopy top for each aircraft can also be used to estimate the downwind distance from the last upwind swath in the spray block to a point where the minimum deposition (trough) is greater than 20 drops per square centimeter. In Figure 3, the deposition level in the second trough is slightly greater than 20 drops per square centimeter and this distance is 484 meters downwind from the last upwind swath. Table 6 gives these distances for all the aircraft and meteorological regimes. The last column in Table 6 shows the number of swaths downwind from the upwind edge of the spray block before the deposition level exceeds 20 drops per square centimeter.

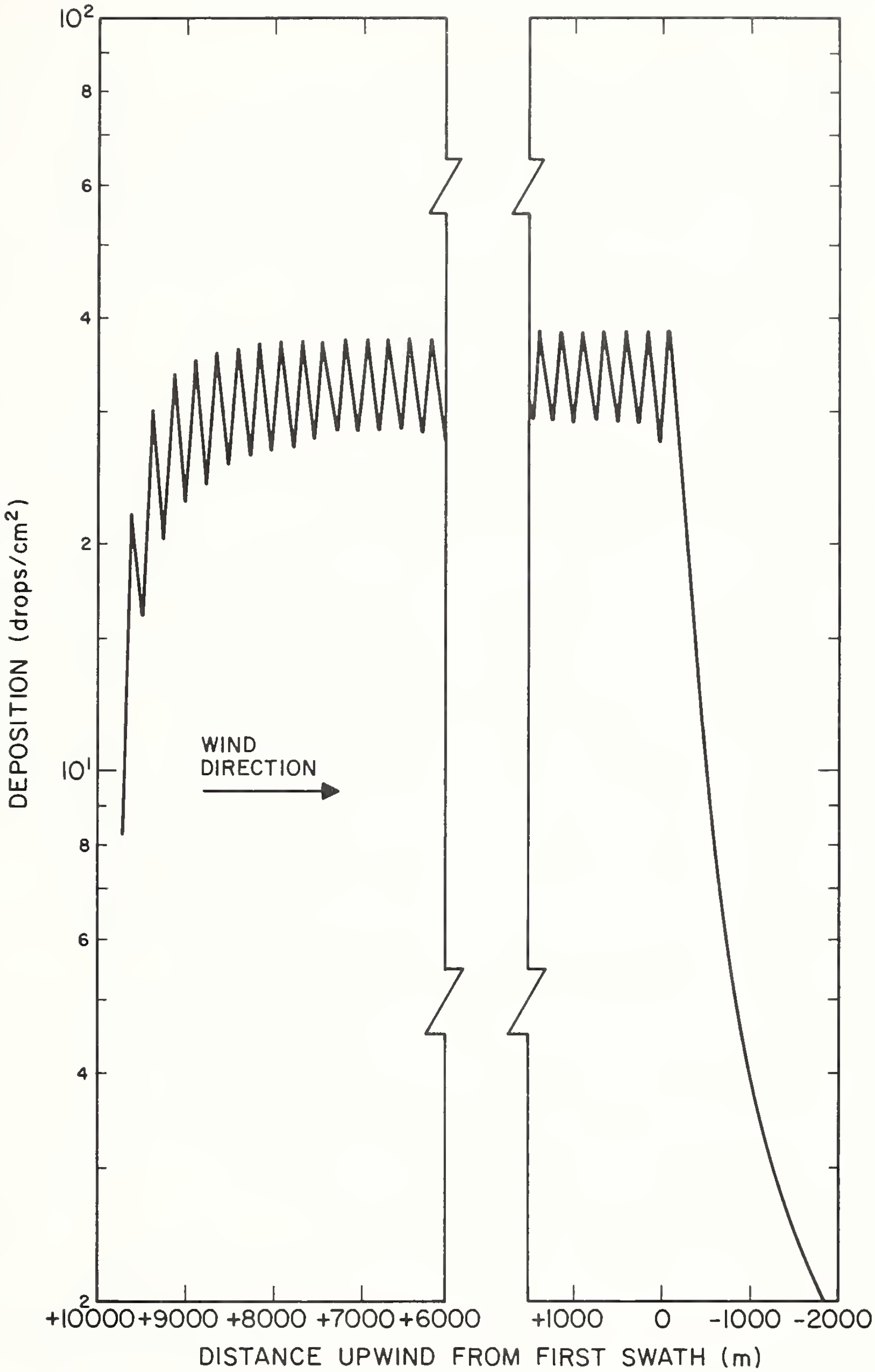

Figure 3. Calculated deposition levels over the forest canopy for a C-54 aircraft spraying Sevin 4-oil in the early morning under very light wind speeds.

Table 5. Optimum swath widths and application rates.

Aircraft Type	Time of Morning	Wind Speed Category	Swath Width (m)	Swath Width (ft)	Application Rate (oz/acre)	Aircraft Height Above Canopy (m)	Aircraft Height Above Canopy (ft)
TBM	Early	Very Light	67	220	64	30.5	100
		Light	122	400	64	30.5	100
	Late	Light	73	240	64	30.5	100
		Moderate	122	400	64	30.5	100
C-54	Early	Very Light	244	800	20	61	200
		Light	366	1200	20	61	200
	Late	Light	201	660	20	61	200
		Moderate	366	1200	20	61	200
Constel-lation	Early	Very Light	244	800	12	61	200
		Light	366	1200	12	61	200
	Late	Light	198	650	12	61	200
		Moderate	274	900	12	61	200
Bell 205	Early	Very Light	23	75	70	15.2	50
		Light	52	170	70	15.2	50
	Late	Light	30	100	70	15.2	50
		Moderate	61	200	70	15.2	50
Thrush	Early	Very Light	23	75	120	15.2	50
		Light	43	140	120	15.2	50
	Late	Light	30	100	120	15.2	50
		Moderate	61	200	120	15.2	50

Table 6. Downwind distances from the last swath to the point where deposition exceeds 20 drops per square centimeter.

Aircraft Type	Time of Morning	Wind Speed Category	Distance (m)	Distance (ft)	Number of Swath Widths
TBM	Early	Very Light	134	440	2
		Light	364	1194	3
	Late	Light	222	728	3
		Moderate	514	1686	4
C-54	Early	Very Light	484	1588	2
		Light	734	2408	2
	Late	Light	944	3097	5
		Moderate	2281	7483	6
Constel-lation	Early	Very Light	724	2375	3
		Light	1826	5991	5
	Late	Light	988	3241	5
		Moderate	1706	5597	6
Bell 205	Early	Very Light	68	223	3
		Light	208	682	4
	Late	Light	155	509	5
		Moderate	436	1430	7
Thrush	Early	Very Light	48	157	3
		Light	93	305	2
	Late	Light	99	325	3
		Moderate	256	840	4

Spray Deposition Within the Forest Canopy

The canopy penetration model and forest characteristics were used to estimate the average fraction of the deposition level presented at the top of the canopy that impacted on the trees and did not reach the ground. The results are presented in Table 7. For a given aircraft (drop-size distribution held constant), Table 7 shows, as expected, that the higher the wind speeds in the canopy, the greater the number of drops that impact on the trees.

Spray Drift

The CBG dispersion model was also used to estimate the drift deposition, peak concentration and total dosage downwind from the downwind edge of the spray block for all the aircraft types and meteorological regimes using the optimum swath widths and application rates given in Table 5. The results of the deposition drift calculations are given in Table 8 at downwind distances of 0.25, 0.5, 1, 1.5, 2, 3, 4 and 6 miles. The last column of Table 8 gives the downwind distance to the point where the deposition level falls below 1 drop per square centimeter. As Table 8 shows, this distance can be as great as 54 kilometers downwind from the block for the Constellation aircraft spraying in the late morning under moderate wind conditions. It should be noted, however, that the drops reaching these longer downwind distances are small and mass deposition falls off very rapidly with distance. For example, Figure 4 shows mass and drop deposition levels downwind from the spray block for the C-54 aircraft spraying during the early morning under very light wind conditions. In the figure, the peak deposition downwind from the spray block is about 34 drops per square centimeter or 23 ounces per acre. At 10 kilometers downwind from the spray block, the deposition level in drops per square centimeter has decreased by a factor of 25 to about 1.36 drops per square centimeter, but the mass deposition has decreased by a factor of 230 to about 0.1 ounces per acre.

Tables 9 and 10 show the peak concentration (the highest calculated concentration) and dosage (concentration integrated over the spray cloud passage time from all flight paths) at the same downwind distances from the spray block as in Table 8.

CONCLUSIONS

We believe the results of the model calculation presented above illustrate the effects of meteorology, aircraft type, and spray distributions on the effectiveness of spray applications over a forest canopy and also illustrate the usefulness of modeling techniques in planning and conducting spray operations. Optimum swath widths and application rates are very sensitive to the values of the input parameters used in the calculations. The results presented in this report therefore should not be assumed to apply to other types of aircraft, spray systems, spray material, forest characteristics or meteorological regimes.

Table 7. Deposition in the canopy.

Aircraft Type	Time of Morning	Wind Speed Category	Average Level at Canopy Top (drops/cm^2)	Average Level Deposited In the Canopy (drops/cm^2)	Collection Efficiency (%)
TBM	Early	Very Light	32.0	1.71	5.4
		Light	32.0	5.69	17.8
	Late	Light	32.0	4.07	12.7
		Moderate	32.0	12.47	39.0
C-54	Early	Very Light	34.4	1.52	4.4
		Light	34.4	4.65	13.5
	Late	Light	34.4	3.51	10.2
		Moderate	34.4	10.22	29.7
Constel-lation	Early	Very Light	37.2	1.92	5.2
		Light	37.2	4.51	12.2
	Late	Light	37.2	3.04	8.2
		Moderate	37.2	9.44	25.4
Bell 205	Early	Very Light	31.6	2.14	6.8
		Light	31.6	6.73	21.3
	Late	Light	31.6	4.27	13.5
		Moderate	31.6	11.49	36.3
Thrush	Early	Very Light	32.2	2.64	8.2
		Light	32.2	6.70	20.8
	Late	Light	32.2	5.48	17.0
		Moderate	32.2	14.40	44.7

Table 8. Deposition (drops/cm^2) at selected distances downwind from the spray block.

Aircraft Type	Time of Morning	Wind Speed Category	Distance Downwind from Spray Block in Miles (KM)								Downwind Distance to 1 drop/cm^2
			0.25 (0.4)	0.5 (0.8)	1.0 (1.6)	1.5 (2.4)	2.0 (3.2)	3.0 (4.8)	4.0 (6.4)	6.0 (9.7)	(km)
TBM	Early	Very Light	5.7	3.8	3.0	2.3	1.8	1.2	0.9	0.5	5.9
		Light	11.1	5.3	3.5	3.0	2.5	1.9	1.5	1.0	9.6
	Late	Light	7.8	4.3	3.1	2.9	2.7	2.4	2.0	1.5	15.0
		Moderate	13.3	5.9	3.0	2.3	2.0	1.9	1.9	1.9	23.3
C-54	Early	Very Light	19.4	10.5	7.5	5.7	4.5	3.1	2.3	1.4	13.3
		Light	28.1	15.8	9.2	7.5	6.4	4.7	3.7	2.4	21.2
	Late	Light	18.4	10.1	7.0	6.3	6.0	5.2	4.5	3.3	29.3
		Moderate	23.1	13.1	6.4	4.8	4.2	4.0	4.0	3.6	42.5
Constellation	Early	Very Light	21.2	13.4	10.3	8.2	6.8	4.9	3.7	2.4	20.2
		Light	26.1	16.9	11.5	9.8	8.5	6.6	5.3	3.7	29.0
	Late	Light	17.1	11.1	8.7	8.2	7.9	7.0	6.1	4.6	37.7
		Moderate	18.1	10.6	6.2	5.0	4.7	4.7	4.8	4.5	53.9
Bell-205	Early	Very Light	4.7	3.5	3.0	2.3	1.8	1.2	0.9	0.5	5.9
		Light	6.7	3.5	2.6	2.4	2.0	1.5	1.2	0.8	8.2
	Late	Light	3.8	2.0	1.5	1.6	1.7	1.6	1.4	1.0	9.9
		Moderate	6.7	2.8	1.1	0.7	0.6	0.7	0.8	0.9	1.9
Thrush	Early	Very Light	4.0	3.5	2.6	1.9	1.5	1.0	0.7	0.4	4.8
		Light	4.8	2.8	2.4	2.0	1.7	1.2	0.9	0.6	5.9
	Late	Light	3.0	1.6	1.4	1.4	1.4	1.2	1.0	0.8	7.0
		Moderate	6.0	2.3	0.9	0.6	0.5	0.6	0.7	0.7	1.5

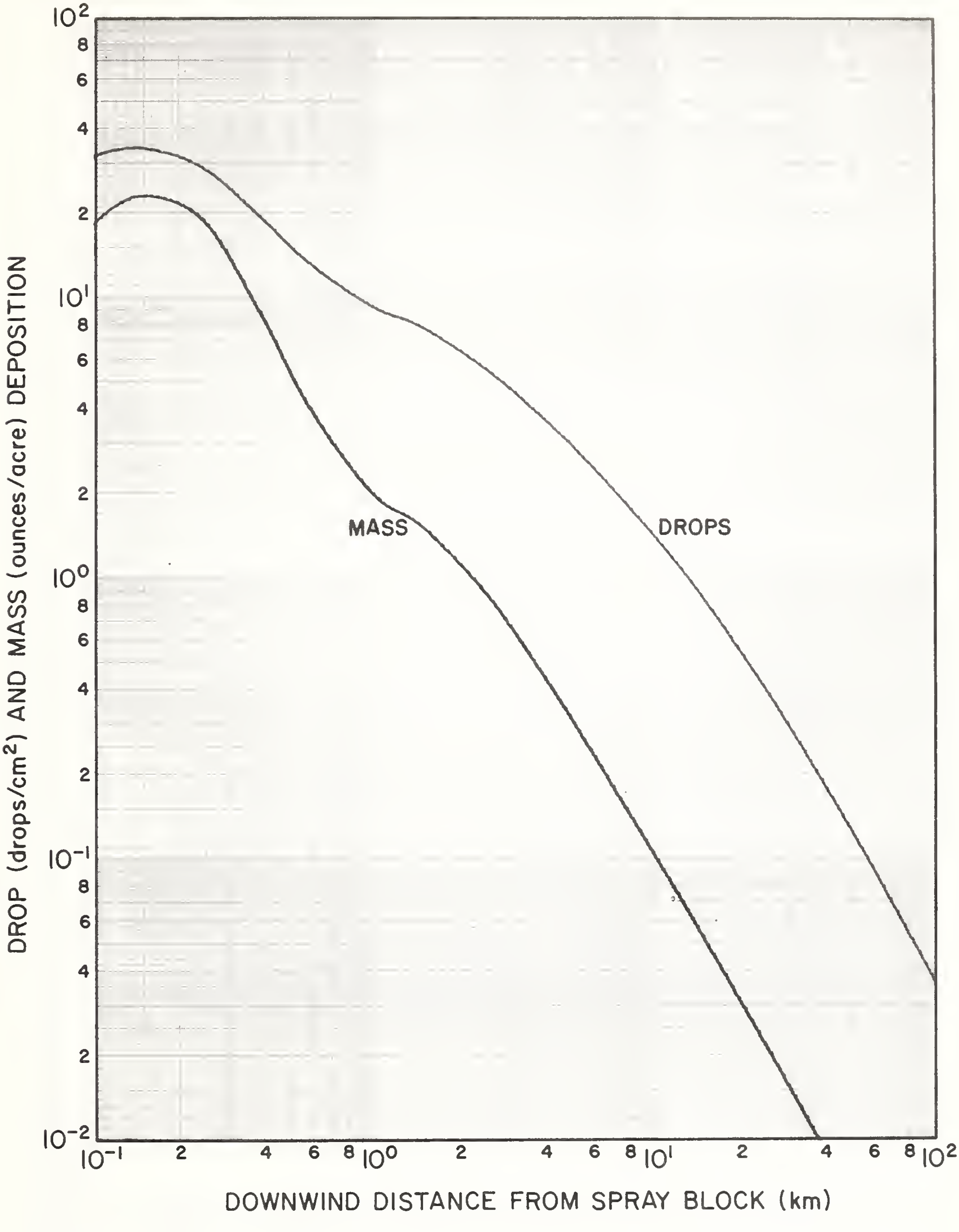

Figure 4. Drop and mass deposition due to drift downwind from a C-54 aircraft spraying Sevin 4-oil during the early morning under very light conditions.

Table 9. Peak concentration (drops/$cm^3 x10^{-4}$) at selected distances downwind from the spray block.

Aircraft Type	Time of Morning	Wind Speed Category	Distance Downwind from Spray Block in Miles (KM)							
			0.25 (0.4)	0.5 (0.8)	1.0 (1.6)	1.5 (2.4)	2.0 (3.2)	3.0 (4.8)	4.0 (6.4)	6.0 (9.7)
TBM	Early	Very Light	32.7	18.7	11.5	8.36	6.83	4.12	2.91	1.70
		Light	67.3	37.9	21.2	15.5	12.3	8.43	6.24	3.88
	Late	Light	54.1	30.8	17.2	12.3	9.75	6.91	5.25	3.39
		Moderate	106	58.9	29.7	19.4	14.3	9.38	7.02	4.64
C-54	Early	Very Light	90.9	53.5	31.5	22.7	17.5	11.6	8.44	5.10
		Light	140	97.2	54.4	39.2	30.9	21.3	15.8	9.83
	Late	Light	109	65.7	36.4	26.1	20.8	14.9	11.4	7.40
		Moderate	152	110	56.5	36.8	27.1	17.9	13.6	9.18
Constellation	Early	Very Light	129	81.2	49.9	36.9	29.0	19.7	14.4	8.78
		Light	183	129	77.5	57.7	46.3	32.6	24.5	15.6
	Late	Light	132	83.6	48.9	36.0	29.1	21.2	16.4	10.8
		Moderate	183	123	66.3	44.5	33.4	22.7	17.6	12.1
Bell-205	Early	Very Light	47.4	25.7	15.0	10.6	7.97	4.96	3.38	1.86
		Light	82.8	45.5	23.7	16.6	12.8	8.40	6.00	3.54
	Late	Light	59.2	32.6	16.5	11.1	8.45	5.72	4.21	2.58
		Moderate	106	57.6	26.9	16.2	11.1	6.60	4.71	2.98
Thrush	Early	Very Light	28.9	17.2	10.9	7.84	5.42	3.26	2.17	1.16
		Light	55.6	30.1	16.5	11.8	9.04	5.84	4.12	2.37
	Late	Light	43.6	23.5	11.9	8.16	6.30	4.26	3.11	1.90
		Moderate	88.1	45.7	20.9	12.5	8.60	5.14	3.69	2.33

Table 10. Dosage (drop seconds/cm^3) at selected distances downwind from the spray block.

Aircraft Type	Time of Morning	Wind Speed Category	Distance Downwind from Spray Block in Miles (KM)							
			0.25 (0.4)	0.5 (0.8)	1.0 (1.6)	1.5 (2.4)	2.0 (3.2)	3.0 (4.8)	4.0 (6.4)	6.0 (9.7)
TBM	Early	Very Light	1.62	1.28	1.06	0.93	0.83	0.68	0.58	0.45
		Light	1.61	1.26	1.00	0.90	0.82	0.71	0.63	0.52
	Late	Light	1.21	0.95	0.75	0.67	0.61	0.55	0.49	0.42
		Moderate	1.08	0.82	0.60	0.49	0.43	0.37	0.33	0.29
C-54	Early	Very Light	4.42	3.55	2.90	2.55	2.30	1.94	1.69	1.35
		Light	3.62	3.16	2.53	2.25	2.06	1.79	1.59	1.31
	Late	Light	2.46	2.00	1.59	1.42	1.31	1.18	1.07	0.91
		Moderate	1.71	1.50	1.12	0.93	0.82	0.70	0.64	0.57
Constellation	Early	Very Light	6.68	5.60	4.70	4.22	3.85	3.30	2.89	2.33
		Light	4.99	4.42	3.71	3.36	3.13	2.77	2.49	2.08
	Late	Light	3.17	2.65	2.19	1.98	1.86	1.69	1.55	1.34
		Moderate	2.07	1.76	1.35	1.15	1.03	0.90	0.84	0.75
Bell-205	Early	Very Light	1.78	1.29	1.03	0.90	0.80	0.65	0.55	0.41
		Light	1.53	1.11	0.81	0.71	0.64	0.55	0.49	0.39
	Late	Light	1.01	0.73	0.51	0.43	0.39	0.35	0.32	0.27
		Moderate	0.89	0.62	0.41	0.31	0.25	0.20	0.18	0.15
Thrush	Early	Very Light	1.14	0.89	0.74	0.63	0.54	0.43	0.35	0.26
		Light	1.03	0.74	0.57	0.50	0.45	0.38	0.33	0.26
	Late	Light	0.74	0.52	0.37	0.32	0.29	0.26	0.23	0.20
		Moderate	0.73	0.49	0.32	0.24	0.20	0.16	0.14	0.12

LITERATURE CITED

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APPENDIX A

Development of Wind Speed Profiles Used in the Model Calculations

The vertical profiles of wind speed above and below the forest canopy used in the model calculations were developed by matching a power-law wind profile for flat-open areas with profiles for above and below the canopy suggested by Oliver (1971).

The power-law expression for the mean wind speed over flat-open areas is given by the expression

$$\bar{u}\{z\} = \bar{u}_R \left(\frac{z}{z_R}\right)^p \qquad \text{(A-1)}$$

where

$\bar{u}\{z\}$ = mean wind speed at height z
$\bar{u}_R$ = mean wind speed at the reference height z_r
p = power-law coefficient

The zero-plane displacement profile for above the canopy suggested by Oliver (1971) is given by

$$\bar{u}\{z\} = \frac{u^*}{k} \ln\left(\frac{z - D}{z_o}\right) \qquad \text{(A-2)}$$

where

u^* = friction velocity
k = von Karman constant (0.4)
D = zero plane displacement
= $0.75\ H_c$
H_c = canopy height = 15.2 m
z_o = roughness length

In the calculations, z_o was set equal to 0.96 m for early morning and equal to 0.70 m for late morning.

We assume that the mean wind speed $\bar{u}_R$ and the power-law coefficient p shown in Table 1 in the main body of the text, in conjunction with Equation (A-1), describe the wind profile in open areas. Equation (A-2) was set equal to Equation (A-1) at a height of $3H_c$ (see Smith, et al, 1972) above the canopy and a value for the friction velocity u^* was calculated. Using this value of u^*, the profile from $3H_c$ to the top of the canopy was calculated from Equation (A-2). The profile below the canopy was calculated using the wind speed at the canopy top from Equation (A-2) and the normalized wind speed profile in Table A-1. A typical profile obtained by using this procedure is shown in Figure A-1.

Table A-1. Normalized wind speed versus height within the canopy (after Oliver, 1971).

Percent of Canopy Height	Percent of Wind Speed at the Canopy Top
100	100
98.9	94.4
86.6	53.5
71.2	34.4
61.8	22.9
49.5	16.4
37.1	16.4
24.7	21.3
12.4	20.2
6.2	14.7

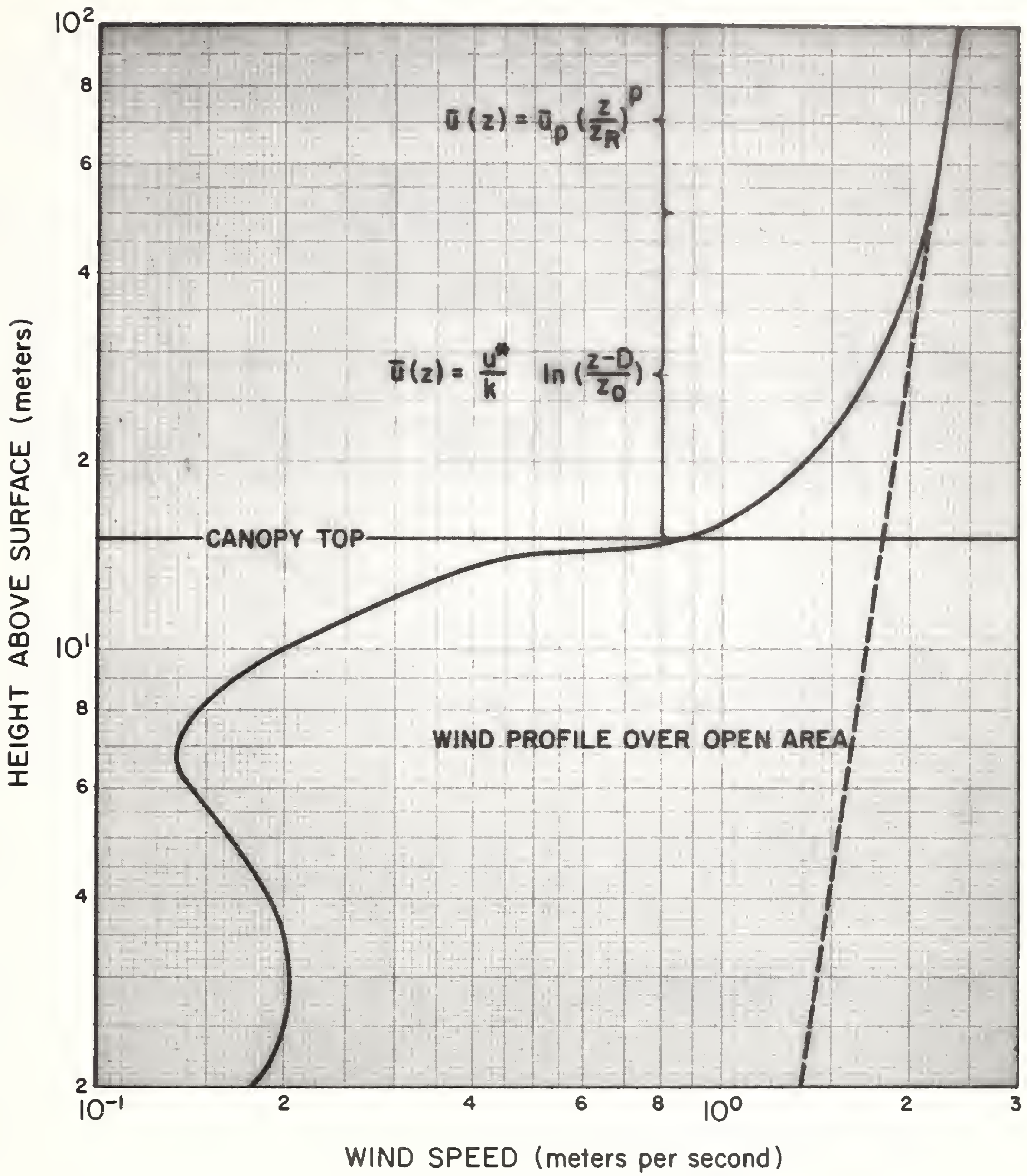

Figure A-1. Wind speed profile within and above the canopy (solid line) for the late morning meteorological regimes with light wind speeds. Dashed line represents the wind profile over an open area.

The transport wind speed $\bar{u}_T$ used in the dispersion model for each aircraft and meteorological regime to represent the mean wind speed above the canopy between the wake vortex stabilization height, b/2, and the aircraft flight altitude, H, is

$$\bar{u}_T = \frac{\bar{u}_1 + \bar{u}_2}{H - (b/2 + H_c)} \tag{A-3}$$

where

$$\bar{u}_1 = \left\{ \begin{array}{ll} 0 & ; \; H \le 3H_c \\ \int_{3H_c}^{H} \left(\frac{z}{z_R}\right)^p dz = \frac{\bar{u}_R}{(1+p)\, z_R^p} \left[H^{1+p} - \left(3H_c\right)^{1+p} \right. & \left. ; \; H > 3H_c\right] \end{array} \right\} \tag{A-4}$$

$$\bar{u}_2 = \int_{H_c+b/2}^{\min\,(H,\, 3H_c)} \ell n \left(\frac{z - D}{z_o}\right) dz$$

$$= \frac{z_o\, u^*}{k} \left[z_u\, \ell n\, z_u - z_u - \left(z_\ell\, \ell n\, z_\ell - z_\ell\right)\right] \tag{A-5}$$

$$z_u = \frac{\min\,(H,\, 3H_c) - D}{z_o} \tag{A-6}$$

$$z_\ell = \frac{H_c + (b/2) - D}{z_o} \tag{A-7}$$

The mean cloud transport speeds $\bar{u}_T$ calculated from Equation (A-3) are presented in Table 2 in the main body of the text.

APPENDIX B

Mass and Number Distributions, Settling Velocities and Reflection Coefficients used in the Model Calculations

Tables B-1 through B-5 give the mass and number distributions, settling velocities and reflection coefficients for the various aircraft. The mass and number distributions for the C-54 and Constellation aircraft were obtained from characterization trial data obtained by the Methods Application Group (MAG) near Mesa, Arizona in 1976 (MAG-2-76). Similar data for the TBM aircraft were obtained by MAG from trials conducted near Mesa, Arizona in 1979 (MAG-2-79). Because no data were available for the Thrush aircraft, we used data from the Pawnee Brave aircraft trials conducted in 1979 near Mesa to represent the Thrush. The data for the Bell 205 aircraft are based on an average distribution fitted by least-squares to 11 characterization trials of the Bell 205 aircraft spraying Dylox conducted during the Northern Region 1976 Pilot Project at Townsend, Montana (Dumbauld and Rafferty, 1976).

The gravitational settling velocities given in the tables were calculated for the mean drop size in each drop-size category using a technique recommended by McDonald (1960) and assuming an air pressure of 990 millibars and temperature of 10 degrees Celsius. The density of Sevin 4-oil is 0.878 grams per cubic centimeter. The reflection coefficients, which depend on the gravitational settling velocity of the drop, were obtained from Figure 3-2 of the report by Dumbauld, Rafferty and Bjorklund (1977).

Table B-1. Mass and number distributions, settling velocities and reflection coefficients used for the TBM aircraft.

Drop-Size Category	Mean Drop Diameter (μm)	Fraction f_j		Settling Velocity V_j (m/s)	Reflection Coefficient γ_j
		Mass	Number		
1	34.0	.00049	.0380	.045	0.64
2	56.6	.009	.1893	.124	0.44
3	82.6	.02	.1082	.211	0.22
4	98.7	.03	.0951	.273	0.07
5	111	.04	.0889	.333	0.0
6	127	.10	.1488	.407	0.0
7	144	.10	.1021	.491	0.0
8	159	.10	.0758	.572	0.0
9	182	.20	.1011	.672	0.0
10	207	.10	.0344	.769	0.0
11	227	.10	.0261	.847	0.0
12	253	.10	.0188	.969	0.0
13	277	.04	.0057	1.09	0.0
14	300	.03	.0034	1.21	0.0
15	331	.02	.0017	1.34	0.0
16	371	.01	.0006	1.50	0.0

Table B-2. Mass and number distributions, settling velocities and reflection coefficients used for the C-54 aircraft.

Drop-Size Category	Mean Drop Diameter (μm)	Fraction f_j		Settling Velocity V_j (m/s)	Reflection Coefficient γ_j
		Mass	Number		
1	36.3	.0068	.1250	.051	0.62
2	51.0	.02	.1353	.100	0.50
3	64.1	.03	.1009	.158	0.36
4	72.9	.04	.0915	.182	0.30
5	82.4	.10	.1583	.209	0.23
6	93.3	.10	.1091	.247	0.13
7	105	.10	.0756	.302	0.0
8	120	.20	.1020	.373	0.0
9	132	.10	.0385	.427	0.0
10	144	.10	.0299	.485	0.0
11	159	.10	.0220	.568	0.0
12	172	.04	.0070	.630	0.0
13	184	.03	.0043	.674	0.0
14	206	.02	.0020	.760	0.0
15	272	.01	.0004	1.05	0.0

Table B-3. Mass and number distributions, settling velocities and reflection coefficients used for the Constellation aircraft.

Drop-Size Category	Mean Drop Diameter (μm)	Fraction f_j		Settling Velocity V_j (m/s)	Reflection Coefficient γ_j
		Mass	Number		
1	35.0	.0135	.1549	.048	0.63
2	45.5	.03	.1567	.080	0.55
3	55.1	.04	.1176	.118	0.49
4	65.9	.10	.1719	.164	0.34
5	77.1	.10	.1073	.196	0.25
6	85.9	.10	.0776	.221	0.20
7	97.2	.20	.1071	.267	0.08
8	108	.10	.0391	.317	0.0
9	117	.10	.0307	.361	0.0
10	129	.10	.0229	.416	0.0
11	142	.04	.0069	.480	0.0
12	153	.03	.0041	.539	0.0
13	163	.02	.0023	.594	0.0
14	174	.01	.0009	.641	0.0

Table B-4. Mass and number distributions, settling velocities and reflection coefficients used for the Bell-205 helicopter.

Drop-Size Category	Mean Drop Diameter (μm)	Fraction f_j		Settling Velocity V_j (m/s)	Reflection Coefficient γ_j
		Mass	Number		
1	34.7	.0009	.0726	.046	0.63
2	51.3	.009	.2247	.101	0.50
3	75.1	.02	.1592	.189	0.28
4	94.1	.03	.1214	.251	0.12
5	111	.04	.0986	.329	0.0
6	140	.10	.1228	.466	0.0
7	172	.10	.0662	.630	0.0
8	198	.10	.0434	.730	0.0
9	236	.20	.0513	.880	0.0
10	276	.10	.0160	1.08	0.0
11	308	.10	.0115	1.24	0.0
12	352	.10	.0077	1.42	0.0
13	391	.04	.0023	1.56	0.0
14	423	.03	.0013	1.68	0.0
15	462	.02	.0007	1.82	0.0
16	520	.01	.0002	2.04	0.0

Table B-5. Mass and number distributions, settling velocities and reflection coefficients used for the Thrush aircraft.

Drop-Size Category	Mean Drop Diameter (µm)	Fraction f_j		Settling Velocity V_j (m/s)	Reflection Coefficient γ_j
		Mass	Number		
1	34.5	.0005	.0704	.046	0.63
2	63.5	.009	.1993	.157	0.36
3	101	.02	.1117	.282	0.04
4	121	.03	.0970	.377	0.0
5	133	.04	.0960	.436	0.0
6	156	.10	.1497	.555	0.0
7	183	.10	.0921	.677	0.0
8	211	.10	.0605	.784	0.0
9	252	.20	.0705	.966	0.0
10	296	.10	.0219	1.18	0.0
11	336	.10	.0150	1.36	0.0
12	387	.10	.0098	1.56	0.0
13	430	.04	.0029	1.71	0.0
14	459	.03	.0018	1.82	0.0
15	487	.02	.0010	1.92	0.0
16	520	.01	.0004	2.05	0.0